Photon Detectors with Large Dynamic Range and at Near Infrared Wavelength for Direct Detection Space Lidars

Michael A. Krainak[a], Xiaoli Sun*[b], Guangning Yang[b],
Laddawan R. Miko[c], and James B. Abshire[d]
NASA Goddard Space Flight Center, Code [a]554/[b]694/[c]553/[d]690, MD, 20771, USA

ABSTRACT

Space-based lidar instruments must be able to detect extremely weak laser return signals from orbital distance. The signals have a wide dynamic range caused by the variability in atmospheric transmission and surface reflectance under a fast moving spacecraft. Ideally, lidar detectors should be able to detect laser signal return pulses at the single photon level and produce linear output for multiple photon events. They should have high quantum efficiency in the near-infrared wavelength region where high-pulse-energy space-qualified lasers are available. Silicon avalanche photodiode (APD) detectors have been used in most space lidar receivers to date. Their sensitivity is typically hundreds of photons per pulse at 1064 nm, and is limited by the quantum efficiency, APD gain noise, dark current, and preamplifier noise. NASA is investigating photon-sensitive near-infrared detectors with linear response for possible use on the next generation direct-detection space lidars.

We have studied several types of linear mode avalanche photodiode detectors that are sensitive from 950 nm to 1600 nm and potentially viable for near term space lidar missions. We present our measurement results and a comparison of their performance.

Keywords: laser rangers, laser altimeters, photon detectors, APD.

1. INTRODUCTION

NASA has a strong interest in atmospheric backscatter lidars and surface height and reflectance lidars. The latter are often called laser ranging or laser altimeter instruments. This paper gives an overview of some of the linear-mode avalanche photodiode detector technologies for space-borne pulsed-laser altimeters. The measurement precision of a laser altimeter is determined by the laser pulse-width and the receiver signal-to-noise ratio (SNR). The SNR is determined by the magnitude of the detected signal photons and noise photons accumulated over the receiver integration time and the additional noise introduced by the detector. Ideally a laser altimeter detector would be able to detect a single photon and attain the near-ultimate receiver sensitivity. The detector should also have a linear output so that the SNR increases with the received signal pulse energy. In addition, it should have a wide dynamic range such that it can achieve the required SNR under the worst-condition measurement environment without introducing adverse effects under the best-condition measurement environment. For a typical Earth-orbiting laser altimeter, the laser return signal dynamic range spans two to three orders of magnitude due to the atmospheric conditions and rapid changing terrain types of the satellite ground track.

Most of the single photon detectors available today can only detect one photon at a time and have nonlinear effects when there are more photons in a pulse. There are a few single photon detectors that can estimate of the number of photons in the pulse and correct for the nonlinear effect, but they can only do so for a fixed input laser pulse width [1]. A few devices have been reported to resolve photon numbers for multiple photon events, but the dynamic range is still too narrow or the technology is still not mature enough to use in an Earth orbiting laser altimeter [2]. One technique to mitigate this constraint is to reduce the laser pulse energy but increase the laser pulse rate so that the receiver will not saturate on any single laser pulse and achieve the required SNR by averaging the results over repeated measurements.

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The disadvantage of this technique is higher receiver noise due to the much longer receiver integration time. The receiver is also more complicated since it has to record the signal and noise photons at high timing precision and at a high rate. Also, the receiver electronics must process a large amount of data to find the signal.

Analog or linear photodetectors with lower noise floor are more desirable for the laser altimeters. There can be multiple photons in a received pulse and the SNR can be achieved with a single pulse or fewer pulses. The detectors can be configured to detect two or more photon pulses and reject most background photons that usually come as single photon events. Unfortunately, most of the analog photodetectors today have a relatively high noise floor and the minimum detectable signal is hundreds of photons per pulse. There are several new analog photodetectors that exhibit a much higher quantum efficiency, higher gain, and lower noise. Some of them have reported to detect fewer than 10 or even single photon events. We have studied several of these new detectors and compared them with the conventional Si avalanche photodiodes. The results are reported in this paper.

2. NEAR-INFRARED ENHANCED LINEAR-MODE SILICON AVALANCHE PHOTODIODES

All of NASA's space-based laser altimetry missions have used versions of the near-infrared enhanced silicon avalanche photodiode (APD) detector manufactured by PerkinElmer Opto-Electronics Canada (a.k.a. EG&G and formerly RCA) for detecting laser signal returns at 1064 nm wavelength. These missions include NEAR[3], CLEMENTINE[4], MOLA[5-7], ICESAT/GLAS[8,9], CALIPSO[10], MLA[11] and LOLA[12]. The spaceflight optical receivers are based on custom-built improved versions of the commercial Model C30954E APD. The PerkinElmer APD laser receiver characteristics are given in Table 1. A photograph of the Perkin Elmer APD receiver is shown in Figure 1.

APD laser receiver parameter	PerkinElmer
Quantum efficiency at 1064 nm	35-40%
Average gain	100-120
Ionization coefficient ratio	0.008
Responsivity (kV/W)	300
Diameter (microns)	700
Bulk dark current (pA)	50
Total dark NEP averaged over BW (fW/rt-Hz)	40
Bandwidth	140 MHz
Dynamic range (optical intensity)	> 20 dB
Excess Noise Factor	3

Table 1. Characteristics of Perkin-Elmer enhanced silicon avalanche photodiode detector

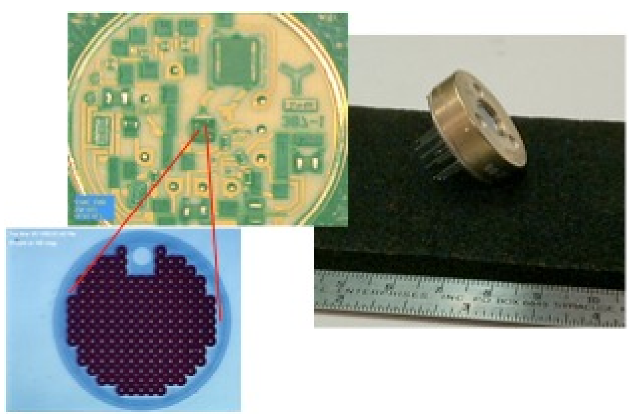

Figure 1. Photograph of PerkinElmer enhanced silicon avalanche photodiode optical receiver

The original Si APD preamplifier module was developed for free space laser communication. It consisted of a near-infrared enhanced Si APD chip, a high voltage regulator circuit and a preamplifier, all on a hybrid circuit inside a 1-inch TO-8 package. The Si APD chip has a guard ring to reduce the leakage current. The high voltage regulator circuit also adjusts its output to compensate for the APD gain and quantum efficiency change over temperature and maintains the overall detector responsivity to within ±10% of the nominal value over a 0 to 40 degree Celsius temperature range. The preamplifier is a high-input-impedance amplifier that has an input current-noise spectral density of about 1.7 pA/rt-Hz and an electrical bandwidth of less than 50 MHz.

A major improvement was made to the detector module during the ICESat/GLAS[8] development - the high input impedance preamplifier was replaced with a transimpedance amplifier. The new preamplifier has a nearly linear phase response. This eliminates under-shoot and over-shoot in the detected pulse waveform. The electrical bandwidth was increased to 140 MHz, with a pulse rise and fall time of 3-4 ns. The overall dark noise was reduced to <1.5 pA/rt-Hz. The transimpedance also has a wider dynamic range than the original high-input-impedance preamplifier. The new detector modules were used in ICESat/GLAS and all subsequent NASA space lidar missions.

The receiver SNR of these detectors can be expressed as the ratio of the mean signal photocurrent to the standard deviation of the noise photocurrent at the output of the preamplifier – all normalized by the APD gain, as

$$SNR \approx \frac{\frac{\eta_{APD} P_{sig}}{hf} q}{\sqrt{2qF\left(\frac{\eta_{APD} P_{sig} + P_{bg}}{hf} + I_{dark}\right) BW_n + \frac{\left\langle I^2_{preamp} \right\rangle}{M^2} BW_n}} \tag{1}$$

where η_{APD} is the APD quantum efficiency; P_{sig}, and P_{bg} are the signal and background light power, respectively; hf is the photon energy; q is the electron charge; I_{dark}, is the detector dark current; F is the APD excess noise factor; $<I^2_{preamp}>$ is the preamplifier input current noise spectral density; BW_n is the receiver noise bandwidth which is usually set to equal to the input signal electrical bandwidth; and M is the average APD photoelectron multiplication gain.

To maximize the receiver SNR, it is desirable to have an optical receiver with a high quantum efficiency and low dark noise detector and a low-noise preamplifier. The APD gain helps to overcome the preamplifier noise but may add excess noise due to the randomness of the gain. Therefore, the usable APD gain is limited by the amount of excess noise it introduces. An APD excess noise factor is defined and approximated as:

$$F \equiv 1 + \frac{\sigma^2_{gain}}{M^2} \tag{2}$$

where σ_{gain} is the standard deviation of the APD gain. The APD excess noise factor may be measured from the mean and standard deviation of the output pulse amplitude at a few known input signal levels and an average gain value. The excess noise factor (for detectors where electrons initiate the avalanche multiplication and carrier independent ionization rates) is given [13] by:

$$F_e(M) = M\left[1 - (1-k)\left(\frac{(M-1)}{M}\right)^2\right] \tag{3}$$

where M is the APD gain and k is the ionization coefficient. Note with k close to zero (ideal), F =2. For silicon APDs, k is 0.008 and F~3 at a gain of 100. For APDs with a higher k value (e.g. InGaAs, InP, InAlAs), the excess noise factors grow much faster with the gain and the optimum APD gain is low (30 to 60) and the preamplifier noise may still be the dominating noise contribution. In InAlAs, F~4 has been achieved [14,15] but only at low gain (~20). Similarly, in InP, F~4 has been achieved[15] but only at low gain (~10). In HgCdTe, the McIntyre carrier-independent (random) ionization rate assumption is not valid. A noise factor, F~1.0 has been observed [16-18] for HgCdTe APD, implying that the avalanche multiplication process is close to deterministic. The optimum APD gain in this case is much higher

(1000 or more) and can result in noise equivalent inputs (NEI) approaching the single photon level [16-19]. There are also InGaAs APD's with much higher gain values that claim[20, 21] single or a few photon detection capability.

It is difficult to separately measure the APD quantum efficiency and the gain. One can only measure the device responsivity, *R*, which is the product of the quantum efficiency, the gain, and the transimpedance amplifier gain, given by:

$$R = \eta_{APD} q M \cdot Z_{preamp} \quad \text{(V/W)} \tag{4}$$

where Z_{preamp} is the preamplifier gain in V/A which can be measured separately. For the PerkinElmer APD's, the quantum efficiency can be determined from a PIN diode grown on the same wafer of the APD's. For separate absorber and multiplication region APD's, such as InGaAs APD's, the quantum efficiency may be determined by measuring the responsivity at the 'punch-through' bias voltage where the gain is known to be equal to unity.

There are two types of APD dark currents, the surface dark noise that is not multiplied by the APD gain and the bulk dark current that is multiplied by the APD gain. The surface dark current usually has little contribution to the overall noise. However, the bulk dark current is a major contributor to the overall noise and sometimes limits the detector performance. The bulk current usually increases with the APD gain and sets another limit to the usable APD gain.
The receiver sensitivity is often measured by the dark noise equivalent power (NEP), which is equal to the total output noise spectral density in V/rt-Hz divided by the device responsivity in V/W under dark noise only conditions. The dark noise NEP include effects of both the APD bulk dark current, the excess noise factor, and the preamplifier noise, as

$$NEP_{dark} = \left(2qF \cdot I_{dark} + \frac{\left\langle I_{preamp}^2 \right\rangle}{M^2} \right)^{1/2} \cdot \frac{hf}{\eta_{APD} \cdot q} \tag{5}$$

The NEP sets the noise floor and the excess noise factor determines how fast the SNR increases with the signal. Together they determine the receiver sensitivity. For the PerkinElmer Si APD's in ICESat, the dark NEP is about 0.04 pW/rt-Hz.

To further improve the receiver sensitivity, we need higher quantum efficiency, higher APD gain, lower excess noise factor, and lower dark currents than those given in Table 1. A comparison of the device characteristics of various APD's is given in Table 2.

APD laser receiver parameter	Silicon	HgCdTe [Rothman]	HgCdTe [Beck]	HgCdTe [Asbrock]	InAlAs [Asbrock]	InAlAs [Campbell]	InP [Ng]
Quantum efficiency at 1064 nm	35%	50%	(80%)		90%		
Average gain	120	5000	1000	200	75	20	10
Ionization coefficient ratio	0.008	0.00	0.00			0.11	0.4
Responsivity (kV/W)	200	N/A					
Diameter (microns)	700	200	64	20	20	160	
Total NEP averaged over BW (fW/rt-Hz)	30						
NEI (photons)		<1	7.5	1	<20		
Bandwidth (MHz)	140	145	400	1000	1500		
Dynamic range (optical intensity)	> 20 dB	-			>20 dB		
Excess Noise Factor	3	1.2	1.2			4	4

Table 2. Parameters from the open literature on representative APDs or APD-based optical receivers.

3. NASA laser altimetry optical receiver detector diameter requirements

NASA-GSFC has initiated an investigation for possible alternative avalanche photodiode detectors in an attempt to improve the laser receiver performance. There is strong motivation to improve the optical receiver performance since any sensitivity improvements at the receiver directly reduce the required laser pulse energy (assuming all other system component specifications held constant). For the ICESat2 mission, the detector diameter requirement may be changed from ICESat/GLAS (ICESat1). The laser altimeter instrument optical design is typically to image the laser footprint of the surface of interest (e.g. Earth ice sheet) to the detector plane. To insure that the majority of the reflected laser signal energy is collected by the receiver telescope, the altimeter optical receiver field-of-view is typically larger that the laser footprint. This is especially important because the altimeter transmitter-receiver bore-sight alignment varies with temperature (orbital location). The present plan is to use a bore-sight alignment mechanism (BAM) in the outgoing laser transmitter optical path on ICESat2. ICESat1proved one can a 170 micron diameter detector and maintain bore sight alignment with the use of a beam steering mechanism. Therefore, it is possible to reduce the ICESat II 1064 nm channel receiver detector diameter to 200 microns. It still may be desirable to use a larger (e.g. 300 micron) APD diameter to provide bore-sight alignment margin. Reducing the detector diameter requirements introduces the possibility of alternative APD materials because a smaller diameter should allow higher bandwidth and lower noise. In addition, thermo-electric coolers can be incorporated in the optical receiver to reduce the Johnson noise.

4. NASA program linear-mode APDs

The enhanced silicon APD with 35% quantum efficiency leaves room for significant improvement. Greater than 90% quantum efficiency has been achieved in InGaAs, InGaAsP, InAlAsP and HgCdTe semiconductor APDs. These APDs are continuously improving in performance and have a strong expectation for high reliability. The major challenge is to achieve a low NEP and APD gain excess noise factor with an optical receiver based on a 200 micron diameter APD.

In Phase I of our competitive alternative detector development program, we asked US industry to provide the best possible APD-based optical receiver with cost and sixty-day schedule constraints. Due to procurement and contract delays, at this writing, we have received two (of five) Phase I alternative detector devices. Table I shows a comparison of the vendor measured parameters to our measurements of the long-standing well-developed silicon APD. The initial results are attractive. As anticipated, alternative devices that use lower band-gap semiconductors have much higher quantum efficiency. The key APD receiver performance parameters are the noise equivalent power averaged over the detector bandwidth and the excess noise factor. Because of the tight schedule, both alternative devices are limited by the noise from the hybrid trans-impedance amplifier (TIA). We anticipate improvements in this area with time and funding. We have not yet measured the excess noise factor for these devices.

APD laser receiver parameter	PerkinElmer	InGaAs1	InGaAs2
Quantum efficiency at 1064 nm	35%	80%	54%
Average gain	120	30	
Ionization coefficient ratio	0.008		
Responsivity (kV/W)	200	219	406
Diameter (microns)	700	200	200
Total NEP averaged over BW (fW/rt-Hz)	30	81	20
Bandwidth	140 MHz	189 MHz	158 MHz
Dynamic range (optical intensity)	> 20 dB	22 dB	>20 dB
Excess Noise Factor	3	TBD	TBD

Table 3. Comparison of APD laser receiver parameters for in-hand Phase I program device

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